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Determination of Left Ventricular Volumes With Use of a New Nongeometric Echocardiographic Method: Clinical Validation and Potential Application

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A new nongeometric echocardiographic technique for measurement of right and left ventricular volumes was recently validated in vitro. With this method, all images are taken from one point on the chest wall as the transducer is tilted through the ventricle. This approach offers several advantages. No geometric assumptions about ventricular shape are made. All images are acquired from the best echocardiographic window. Furthermore, the digitized points can be used to make a three-dimensional reconstruction of the ventricle.

The present study addresses the clinical feasibility of imaging the heart from a single pivoting point in short axis and compares the accuracy of the method in determining left ventricular volumes with that of biplane cineangiography. Twenty-four patients underwent echocardiographic studies within 2 h before angiography. At catheterization, volumes determined by the biplane area-length method ranged between 95 and 368 ml at end-diastole and between 15 and 303 ml at end-systole. A good correlation was observed between ventricular volumes by angiography and echocardiography at end-diastole and end-systole (r = 0.92 and 0.96, respectively). Correlations between volumes by the two techniques were equally good in patients with wall motion abnormalities (n = 13; r = 0.97). Ventricular ejection fraction ranged between 18% and 84% at angiography and correlated well with echocardiographic measurements (r = 0.82).

Thus, the echocardiographic tilt method provides accurate determination of left ventricular volume and ejection fraction. This nongeometric method offers the potential for the determination of right ventricular volume and three-dimensional display of the heart.

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Alterations in left ventricular volume or shape, or both, are known to occur in response to various disease states such as ischemic heart disease, cardiomyopathy and valvular heart disease. We recently validated (1) a new nongeometric echocardiographic technique for measuring heart volume in vitro. With this method, all echocardiographic images are taken from one point on the chest wall as the transducer is tilted through the ventricle. This approach has several theoretical advantages over existing methods. First, any point on the chest wall that allows scanning of the entire ventricle can be used (1). Second, in contrast to several methods applied to echocardiography for deriving ventricular volumes (2–8), the mathematical treatment of the data makes no assumptions about the geometry of the object being imaged. The potential therefore exists for accurate volume determination of both right and left ventricles, with or without distortion of ventricular shape. Finally, a major advantage of this technique is that it allows for a three-dimensional display of the heart.

The purpose of the present study was 1) to assess the clinical feasibility of imaging the heart with two-dimensional echocardiography from a single pivoting point, and 2) to compare the accuracy of this method of determining left ventricular volumes with that of biplane cineangiography in patients undergoing cardiac catheterization.

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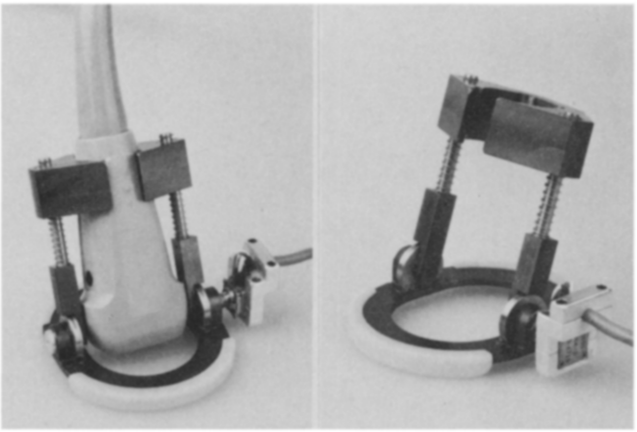


Figure 1. Photographs of the echocardiographic tilt device with **(left)** and without **(right)** a mounted ultrasound transducer. A potentiometer at the right in each picture is connected to the pivot point of the tilting device to measure the angle of tilt. The angle of tilt is zero when the tilting plane is perpendicular to the plane of the base; positive or negative angulation occurs when the tilt plane is deviated to the right or left of the zero position.

Methods

Study patients. The study patients consisted of 30 consecutive patients who underwent both cardiac catheterization with biplane left ventricular cineangiography and echocardiographic tilt studies at The Methodist Hospital between July 1987 and October 1988. None of these patients had been previously screened for quality of echocardiographic study. All patients had given written informed consent for participation in the study, which was approved by the institutional review board at Baylor College of Medicine. The echocardiographic studies were performed ≤2 h and the majority (80%) ≤1 h before cardiac catheterization. Two patients were excluded because of technically difficult echocardiographic studies, and four because of technically difficult left ventricular angiographic studies (two of the latter four patients had ventricular tachycardia during angiography, one had multiple premature ventricular contractions and one had inadequate opacification of the left ventricle).

The remaining 24 patients constituted the study group. There were 19 men and 5 women with a mean age of 57 ± 12 years (range 36 to 74). Twenty-three patients underwent cardiac catheterization for the evaluation of chest pain or angina, and one patient because of suspected severe aortic insufficiency. Twelve patients had a history of previous myocardial infarction, six had previous coronary artery bypass surgery and eight had a history of hypertension. All 24 patients were in sinus rhythm.

Echocardiographic studies. All echocardiographic studies were performed with a Hewlett-Packard Ultrasound system, model 77020A, equipped with a 2.5 MHz transducer. A tilt frame was specially designed to house the transducer by one of the authors (J.C.B.) and Med-Tec, Inc. (Fig. 1). This mounting device secured the transducer position as it was tilted from one echocardiographic plane to another, around a pivot axis. In addition, it allowed the imaging surface of the transducer to be at the same level below the pivot point and maintained the imaging plane perpendicular to that of transducer tilt. The tilting device is equipped with a potentiometer interfaced with the ultrasound machine to allow simultaneous display of the echocardiographic image and the angle of tilt in the right upper corner of the screen (Fig. 2). The angle of tilt is zero when the tilting plane is perpendicular to the plane of the base; positive or negative angulation arises when the tilt plane is deviated to the right or left of the zero position.

In this study, we investigated the feasibility and accuracy of the tilt method from the left parasternal position, scanning the ventricle in short axis. All echocardiographic studies were obtained with the patient in the left lateral recumbent position and were performed by the same observer (W.A.Z.). The best echocardiographic window that allowed imaging the left ventricle in a sweep from base to apex was determined from multiple positions in the parasternal area. Once the best window was identified, usually close to the mitral valve level, a slow sweep from the level of the aortic valve to the apex was performed without altering the patient's respiratory pattern. The sweep speed was slow enough to allow recording of at least two cardiac cycles per tomographic plane; consecutive planes being spaced by approximately 3° to 5° in sweep angulation. Three to five full echocardiographic sweeps were recorded on 0.50 in video tape with a Panasonic 6300 video tape recorder.

The mounting device, which measured 8.5 by 7.0 cm at its base, was very stable on the chest wall. No rocking motion of the casing was observed during the sweeps. To prevent the casing from sliding on the chest wall while the transducer was tilted, the base of the mounting device on the chest wall was held with one hand, and the mounted transducer with the other hand. The offset from the pivoting point to the contact of the transducer with the skin, which is needed to derive volume by the tilt method, was measured with a small ruler and ranged between 1.1 and 1.4 cm (mean 1.3).

The Echocardiographic Tilt Method

Mathematical basis. The mathematical considerations for determining volumes with the nongeometric tilt method were first described by Watanabe et al. (9). Briefly, the transducer is placed in a cylindrical coordinate system (Fig. 3). The angle ϕ is the angle of tilt of the transducer; ρ and Z are the coordinates in the two-dimensional imaging plane emanating from the transducer position at the angle of tilt ϕ. With use of calculus, the volume of any object imaged is the integral over the three dimensions of ρ, Z and ϕ. When the integrals are solved, two equations result: equation 1, to calculate a value called U (in ml/radian; 1 radian = 57.30° angle) from

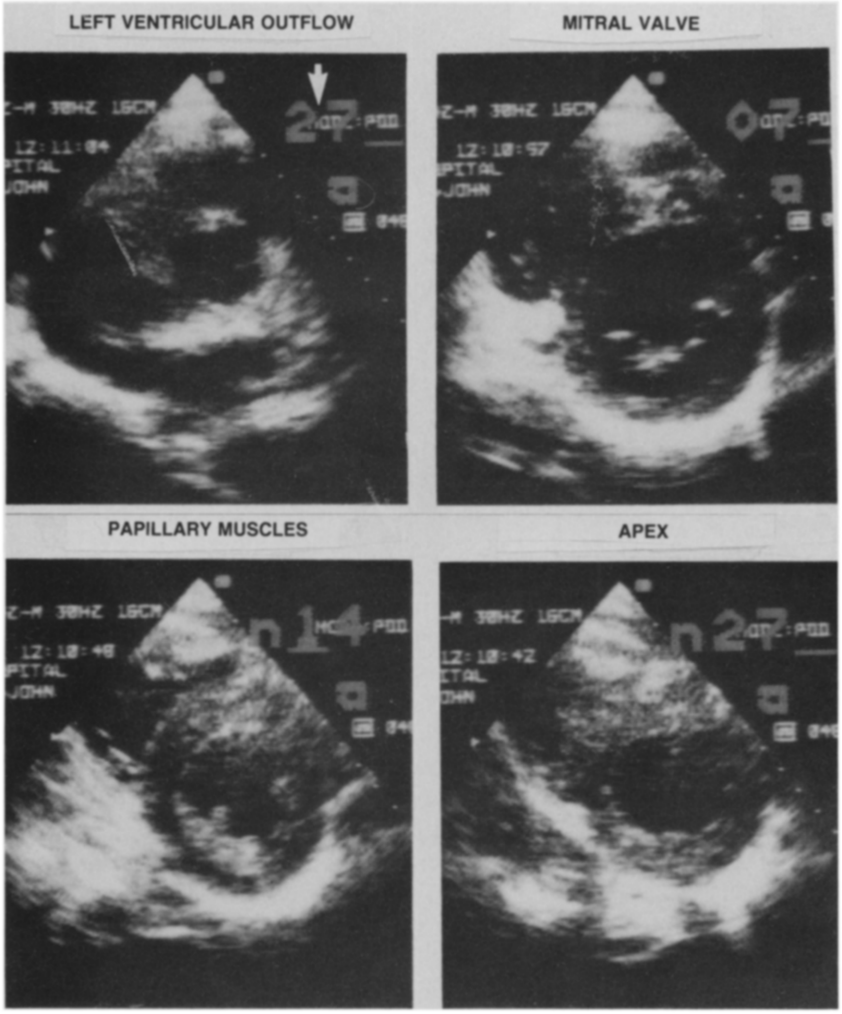


Figure 2. Four echocardiographic end-systolic frames at various levels of the left ventricle obtained by tilting the transducer from a single position in the parasternal area. The number at the upper right of each screen depicts the angulation of tilt in degrees for the respective imaging plane. This angle is highlighted with an **arrow** in the panel at top left. Negative angulation is designated by the letter "n" preceding the angle number. The angles shown for each position are: left ventricular outflow, 27°; mitral valve, 7°; papillary muscles, −14°; apex, −27°.

each echocardiographic image, and equation 2, to derive the volume as the sum of these U values over the total angle that the transducer has covered to image the given structure. The mathematical derivations are shown in the Appendix and have been previously reported in detail (1,9).

The values of U are calculated in a similar way to calculating a cross-sectional area. The endocardial outline is manually traced with a graphics tablet. The resulting value of U can be thought of as the volume contained within the wedge formed by the two successive imaging planes with a sector angle ϕ. Each U value is calculated at a particular value of ϕ. These U values can be plotted against the angles at which they occur to produce a U-ϕ curve (Fig. 4). This curve, in essence, displays the volume distribution in the chamber imaged. For example, Figure 4 displays the volume distribution of the left ventricle (Case 1) when imaged in a short-axis sweep; a precipitous increase in volume distribution occurs from the aortic anulus toward the mitral level, with a gradual decline in volume distribution toward the apex. The area under the U-ϕ curve is the volume of the chamber imaged.

Left ventricular volumes by the tilt method. The echocardiographic studies were analyzed at the University of Texas Southwestern Medical Center by an independent observer unaware of the patients' clinical status and angiographic findings. The images were analyzed on an off-line station (Microsonics model 888) that allowed digitization of the video signal and was equipped with an XY digitizer and customized software for the determination of volumes by the tilt method. A search module allowed frame by frame bidirectional playback of the recorded images.

The sweep that showed the best endocardial definition from base to apex was chosen for determination of left ventricular volumes. The selected cardiac cycles were digitized and played in a continuous loop format, which provided easier definition of the endocardial contour. The most basal image was taken at the level of the aortic anulus, and the most apical image at the level where apical motion is last seen. We have previously demonstrated in vitro that, between these two landmarks, frames spaced by up to 7.5 to 10° intervals allowed accurate determination of volumes (1). In this study, the mean minimal angle between slices was 3°,

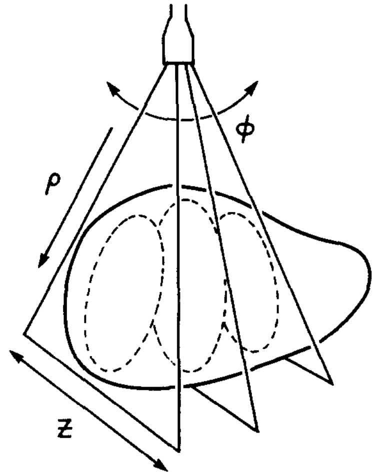
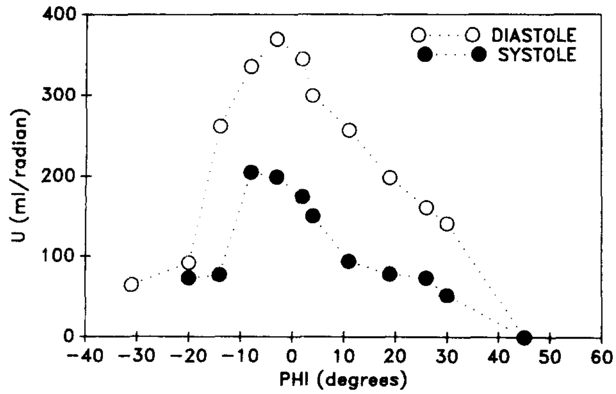


Figure 3. Schematic of the cardiac silhouette with three echocardiographic planes obtained by tilting the transducer from a single position in the short-axis view. A cylindrical coordinate system with the angle of tilt ϕ and the coordinates of ρ and Z are shown. See text for details. (Reproduced from reference 1 9page 228) with permission from the W.B. Saunders Company.)

the mean maximal angle was 10° and the overall mean angle between slices was 5°. The total number of echocardiographic slices of the left ventricle ranged between 8 and 13 (mean 11).

For each imaging plane with a known angle ϕ, the endocardial contours were digitized at end-diastole and end-systole. End-diastole was defined as the frame showing the largest left ventricular cavity, usually at the peak of the electrocardiographic R wave. End-systole was defined as the smallest ventricular cavity, usually just after the peak of the T wave. At the level of the aortic anulus, the anulus itself was digitized. At the level of the left ventricular outflow tract

Figure 4. An example of a U versus ϕ (PHI) curve of Patient 1 at end-diastole and end-systole. The more negative angles are those closer to the aortic anulus and the larger positive angles those toward the cardiac apex. The ventricular volumes at end-diastole and end-systole are calculated as the area under each respective curve.



where only the anterior leaflet of the mitral valve is imaged, the area digitized included the anterior, septal and anterolateral endocardium and the area anterior to a line connecting the outermost right and left edges of the mitral valve. This is because the area posterior to that line actually is in the left atrium. Once the echocardiographic imaging plane started to show posterior left ventricular wall (which usually included structures of the posterior mitral valve leaflet), the whole endocardial contour was included. At the level of the papillary muscles, the papillary muscles were excluded by extrapolation of the adjacent endocardial border in a circular fashion. The results shown for ventricular volumes are derived from an average of two to three determinations of U at each ϕ level.

Biplane Left Ventricular Volumes at Catheterization

Cardiac catheterization was performed immediately after the echocardiographic examination by either the Sones or the Judkins technique. In all patients, biplane left ventricular cineangiography (30° right anterior oblique and 60° left anterior oblique), was performed before coronary angiography. No sedatives or vasoactive drugs were administered between the echocardiographic examination and left ventricular angiography. Forty to 60 ml of Renografin 76 was injected within 3 to 4 s into the left ventricle. The biplane cineangiograms were filmed at 45 frames/s. The exact positions of the table and image intensifier were recorded. To correct for magnification, a biplane cineangiogram of a high precision metallic sphere, 7.62 cm in diameter, was filmed at the exact settings used for the biplane left ventriculogram. The center of the ball was placed at the mid-chest level of the patient. The high resolution metallic sphere has the advantage that it can be imaged with the biplane technique, because any projection will be perpendicular to the maximal known diameter of the sphere.

Only beats in sinus rhythm not preceded by a premature contraction were used for analysis. The contours of the left ventricular silhouette from both projections were traced at end-diastole and end-systole. End-diastole was defined as the frame showing the largest silhouette, and end-systole as the smallest left ventricular silhouette. Left ventricular volumes were determined at end-diastole and end-systole with use of the biplane area-length method corrected for overestimation by the regression equation of Wynne et al. (10). Left ventricular ejection fraction was calculated as the difference between end-diastolic and end-systolic volumes divided by end-diastolic volume. Left ventricular volumes and ejection fraction at cardiac catheterization were determined without the knowledge of echocardiographic volumes or ejection fraction.

Interobserver variability. The interobserver variability in volumes determined by the echocardiographic tilt method

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Table 1. Individual Patient Data (n = 24)

Patient No.	Diagnosis	WMA	Age (yr)/ Gender	Blood Pressure (mm Hg)	Biplane Angiography at Cath VOLED (ml)	VOLES (ml)	EF (%)	Echo Tilt Method VOLED (ml)	VOLES (ml)	EF (%)
1	AI	—	36/M	140/40	260	89	66	255	109	57
2	CAD	—	75/F	140/60	137	46	66	91	34	63
3	CAD	—	50/M	150/84	95	25	74	89	36	59
4	NL	—	69/F	122/70	105	19	82	88	34	61
5	CAD	Post	62/M	140/80	125	49	61	80	30	62
6	CAD	Diff	59/M	100/70	148	108	27	150	104	31
7	CAD	Ant	70/M	120/80	119	34	71	148	50	66
8	CAD	Ant	57/M	145/90	160	73	54	171	79	54
9	CAD	Ant	55/M	120/70	159	71	55	134	65	51
10	CAD	—	56/M	130/70	107	24	78	87	27	69
11	CAD	Ant	64/M	158/80	114	75	34	150	73	51
12	NL	—	40/M	130/90	121	42	65	104	37	64
13	NL	—	64/M	150/80	97	15	84	120	52	57
14	CAD	—	74/M	140/90	101	17	83	100	28	72
15	CAD	Diff	67/M	110/70	211	121	43	194	138	29
16	CM	Diff	51/F	130/90	141	86	39	138	69	50
17	CAD	Ant	43/M	130/80	166	54	67	152	66	57
18	CAD	—	53/M	140/80	184	75	59	194	86	56
19	CAD	Ant	73/F	140/90	118	28	76	119	51	57
20	NL	—	53/F	140/80	130	37	71	65	24	63
21	CAD	Post	66/M	150/94	168	72	57	160	92	42
22	CAD	Inf	54/M	130/80	179	80	55	116	46	60
23	CAD, LVA	Ant	42/M	110/80	368	303	18	396	304	23
24	NL	—	37/M	140/88	159	54	66	144	52	64
Mean			57	133/79	153	66	61	143	70	55
±SD			12	14/12	60	58	18	69	58	12

AI = aortic insufficiency; Ant = anterior; CAD = coronary artery disease; CM = cardiomyopathy; Cath = cardiac catheterization; Diff = diffuse; Echo = echocardiographic; EF = ejection fraction; LVA = left ventricular aneurysm; NL = normal coronary arteries; Post = posterior; VOLED = end-diastolic left ventricular volume; VOLES = end-systolic volume; WMA = wall motion abnormality by angiography.

was assessed in 15 study patients. This was expressed as a linear regression between the two observations and as mean percent error, derived as the absolute difference between observations divided by the mean of the two observations.

Statistical analysis. Results are shown as mean values ± SD. Correlations between left ventricular volumes and ejection fraction at catheterization and those obtained by echocardiography were performed with linear regression analysis.

Results

Clinical feasibility. Echocardiographic imaging in short axis from a single pivot point with the custom frame was feasible in the vast majority of patients. These studies were performed in consecutive patients who were not screened for quality of echocardiographic study. The only two exclusions were one patient with significant emphysema in whom regular parasternal short-axis imaging was difficult, and another patient in whom image quality became unacceptable as the transducer was tilted toward the apex.

Ventricular volumes by echocardiography and angiography. Individual data on the patients studied, including cardiac catheterization and echocardiographic data, are presented in Table 1. Left ventricular volumes at catheterization ranged between 95 and 368 ml at end-diastole and between 15 and 303 ml at end-systole. There was a good correlation between ventricular volumes by angiography and echocardiography for all volume determinations: r = 0.95; $y = 0.95\chi + 8$; SEE = 23 ml (Fig. 5). The correlations were also good when end-diastolic and end-systolic volumes were compared separately (r = 0.92, SEE = 23 ml and r = 0.96, SEE = 16 ml, respectively). The regression equations for the overall comparison and for end-systolic volumes were close to the identity line, with a tendency for underestimation of volumes at end-diastole by echocardiography (Fig. 5).

At catheterization, 13 patients had wall motion abnormalities: 3 with diffuse hypokinesia, 3 with inferoposterior infarction and 7 with anteroapical infarction including 1 patient with a large ventricular aneurysm. In this subgroup of patients with an irregularly shaped or deformed ventricle, volumes by the echocardiographic tilt method correlated

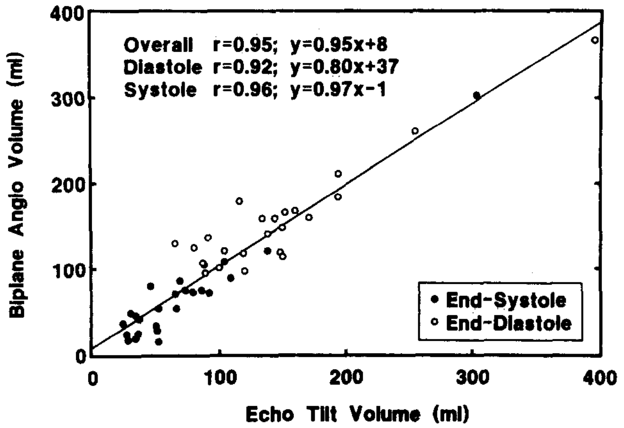

Figure 5. Correlations of echocardiographic (Echo) volumes by the tilt method and left ventricular volumes by biplane cineangiography (Angio). The line of regression for the overall correlation is shown.

well with angiographic results: r = 0.97; y = 0.92χ + 11; SEE = 23 ml.

Left ventricular ejection fraction (in percent) was derived by biplane cineangiography and compared with values obtained by the echocardiographic method (Table 1). Ejection fraction ranged between 18% and 84% at angiography. A good correlation was observed between left ventricular ejection fraction (LVEF) by both methods (r = 0.82; SEE = 10%) with a regression equation close to the identity line [$LVEF_{cath}$ = (1.17 $LVEF_{echo}$) −4].

Interobserver variability. The interobserver variability for determining echocardiographic volumes by the tilt method, expressed as mean percent error, was 10.5% for end-diastole and 16.3% for end-systole (13.4% overall). When the two observers' values were compared with those of linear regression analysis, the correlation coefficient was 0.96 (SEE 15 ml).

Discussion

The present study demonstrates that the echocardiographic tilt method, using a short-axis sweep from base to apex, is feasible in the majority of patients and provides accurate measurements of ventricular volumes and ejection fraction. These findings demonstrate that the tilt methodology is not only theoretically sound (9) and works well in vitro (1), but can be used clinically as well.

Comparison with other methods. Several methods for calculating ventricular volumes have been applied to echocardiography (2–8). The majority of these methods have relied on ideal geometric assumptions of the left ventricle. Of these, the application of Simpson's rule, in its ideal form, requires the fewest assumptions. Inherent to the method is imaging the heart in multiple parallel echocardiographic planes and summing the volumes of the slices; it is a method that has yielded excellent results in the experimental setting (11,12) but usually is not feasible clinically because of chest wall limitations to imaging in parallel sections. A modification to this approach has been applied to clinical echocardiographic imaging (6). The tilt method herein described is similar to the ideal Simpson's rule in that it requires actual sequential tomographic cuts, but it has the advantage of being well suited to echocardiography in that imaging is obtained from the best single acoustic window.

Another advantage of the tilt method is that the derivation of volume requires no assumptions about the geometry of the object being imaged. In this study, results were equally good in patients with and without distortion of left ventricular shape. Because the method is nongeometric, future application to the determination of right ventricular volumes, validated in vitro (1), is promising and would probably depend on image quality.

Limitations and sources of error. During the echocardiographic sweeps in short axis, the image quality typically decreased as the imaging plane approached the apex. However, the amount of volume in the apical region is usually small and errors in endocardial definition at the apex probably have a minor effect on the overall result as demonstrated by the findings in this study. The impact of this error is maximal at end-diastole, when the apical region is closest to the lateral chest wall and harder to visualize; this factor may account in part for underestimation of end-diastolic volumes in some patients.

The number of echocardiographic planes used to determine volumes influences the accuracy of results. An average of 11 echocardiographic planes/patient was used to quantitate volumes in this study. Fewer views could probably have been used because we have previously demonstrated (1) that six to eight planes, spaced by 7.5° to 10°, yield accurate information. Fewer views will probably underestimate volumes, especially if views close to the base and mid-ventricle are omitted, because these contain the largest U values and contribute the most to left ventricular volume.

The tilt method integrates measurements from different echocardiographic planes involving different cardiac cycles and may therefore be affected by factors such as cardiac rhythm and respiration. All patients studied were in sinus rhythm. In this study, we elected to perform the imaging sweeps during unaltered shallow breathing so as to minimize cardiac translation. Simultaneous recording of respiration with cycles chosen during inspiration or expiration may be needed for more refined measurements or other applications of the tilt method. Other sources of error include those pertaining to echocardiographic imaging and arise from outlining the endocardial contours. In this study, the selected cardiac cycles were digitized and played in a continuous loop format, which provided easier definition of the endocardial borders.

Although biplane angiography is the standard for mea-

suring in vivo ventricular volumes, errors still arise from definition of endocardial contours and from geometric assumptions inherent to the area-length method (10,13). Errors may also arise from correction for X ray magnification because the position of the heart in the chest is estimated during imaging of the reference object (metallic sphere or grid). Considering the potential for error in both methodologies, the results obtained in this study support the accuracy of the echocardiographic tilt method for measuring ventricular volumes.

Potential for three-dimensional reconstruction. Three-dimensional echocardiography has been proposed by several investigators and discussed in previous reviews (14,15). The position of the ultrasound transducer in the three-dimensional space needs to be defined so as to display the cardiac images in three dimensions. For this purpose, positioning systems such as a spark-gap or a mechanical arm have been used (16–21). However, these can be complex and cumbersome. Three-dimensional reconstruction has also been performed by measurement of transducer rotation from an apical point (22–24) or by manually aligning short-axis views with a long-axis view (25).

A potential application of the tilt method is three-dimensional reconstruction of the ventricle. The equipment needed is simple and portable. The transducer is easily mounted and dismounted to allow regular clinical imaging in the same setting. Although we have used the data in this study only to validate volume determinations, all the points used are well defined in three-dimensional space in a cylindrical coordinate system. With the appropriate coordinate transformation, the points have been displayed in three dimensions on a graphics workstation.

Conclusions. The tilt method allows for accurate determination of left ventricular volume and ejection fraction in patients with cardiovascular disease. This method is well suited for echocardiography by taking all the images from one point on the chest wall. Furthermore, it allows for a three-dimensional display and is potentially applicable to determination of right ventricular volumes.

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Appendix

In cylindrical coordinates (ρ,ϕ,z), the volume (V) of a region is given by $V = \int\int\int \rho d\rho dz d\phi$, which can be written as $V = \int U d\phi$, where $U = \int\int \rho d\rho dz$.

By definition, the center of mass with respect to the origin of the cylindrical system is $= \int\int \rho d\rho dz / \int\int d\rho dz$ and the sectional area $= \int\int d\rho dz$, so U can be calculated as the product of sectional area and the center of mass for a view.

Further mathematical derivation reveals that, given the points with coordinates (ρ,z) outlining a view:

$$U = \sum_{i=1}^{n} [(\rho_{i+1} + \rho_i)(\rho_{i+1} z_i - \rho_i z_{i+1})/2 + (z_{i+1} - z_i)(\rho^2_{i+1} + \rho_{i+1}\rho_i + \rho^2_i)/3]$$

where n = the number of points of the imaged structure in a view.

Volume is therefore calculated by integrating the values of U over the range of angles ϕ

$$V = \sum_{j=1}^{N} (U_{j+1} + U_j)(\phi_{j+1} - \phi_j)/2,$$

where N = the number of views obtained minus one.

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